

next-generation spintronics. The findings of this work show an efficient route to read and write the bistable AFM state, shedding light on the path toward practical AFM-based spintronics. (Reported by Chang-Yang Kuo, National Yang Ming Chiao Tung University)

*This report features the work of Chang-Yang Kuo, Jan-Chi Yang and their collaborators published in Adv. Mater. **34**, 2200610 (2022).*

TPS 45A Submicron Soft X-ray Spectroscopy TLS 11A1 (Dragon) MCD, MLD, XAS.

- Soft X-ray Absorption
- Materials Science, Condensed-matter Physics

Reference

1. C.-Y. Kuo, Y.-D. Liou, Z. Hu, S.-C. Liao, H.-M. Tsai, H.-W. Fu, C.-Y. Hua, Y.-C. Chen, H.-J. Lin, A. Tanaka, C.-T. Chen, J.-C. Yang, C.-F. Chang, Adv. Mater. **34**, 2200610 (2022).

Weaving Single-Crystal Thin Films

Weave epitaxy: a breakthrough approach to fabrication of twisted lateral homostructures depicts an entirely different conceptual scene for epitaxial growth.

Heteroepitaxy has attracted great interest as it is a key element in modern technologies for delivering high-quality thin films, and it has also been a promising approach to the integration of different materials. Over the past decades, epitaxial growth has enabled the efficient interface and strain engineering of functional materials, which has played a focal role in reinvigorating modern science across a wide spectrum of technically important applications. In terms of epitaxial growth, the selection of single crystal substrates determines the foundation template for the deposited materials. Namely, the lattice constraints and crystalline orientations of deposited materials are subject to the selected template beneath and, thus, the allowed epitaxial degrees of freedom are determined once a specific substrate is chosen. To portray a concrete scenario for epitaxial growth, Jan-Chi Yang (National Cheng Kung University) and his group proposed a new approach, weave epitaxy, to achieve growth of twisted oxide lateral homostructures with multiple conjunction degrees of freedom.

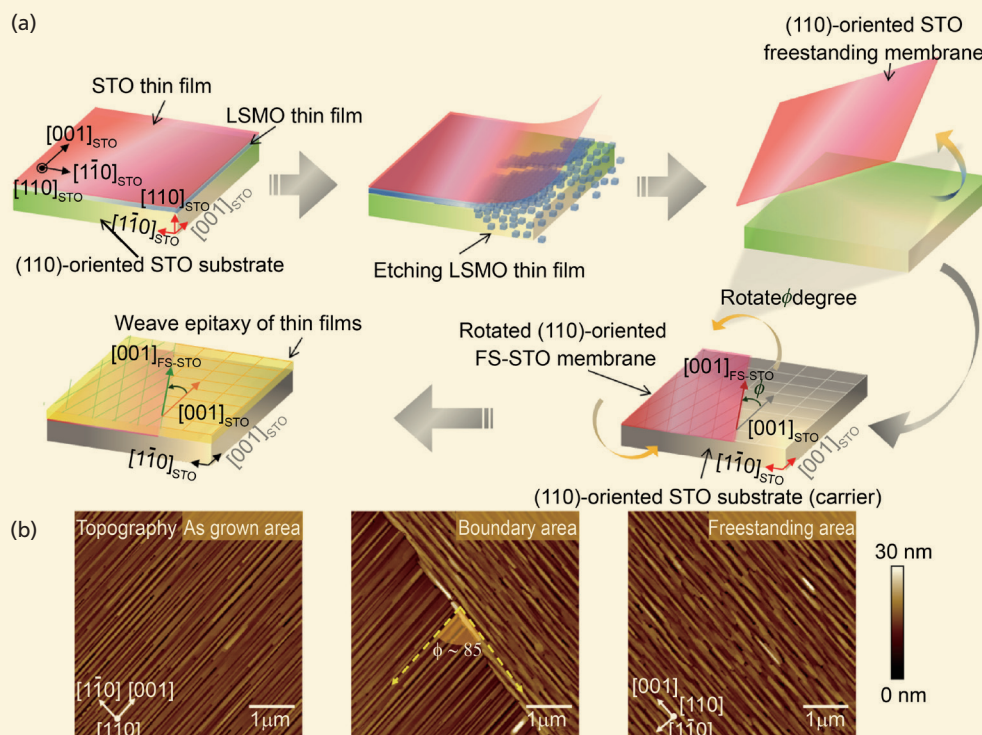


Fig. 1: Twisted oxide lateral homostructures. (a) Schematic illustration of the fabrication of lateral oxide homostructures. (b) Topography images of (110)-oriented BFO grown on FS-STO, the border, and pristine STO regions (from left to right). [Reproduced from Ref. 1]

The detailed fabrication process that they recently established is illustrated in **Fig. 1**. Firstly, an SrTiO_3 (STO) thin film is deposited on a $(\text{La,Sr})\text{MnO}_3$ (LSMO) sacrificial layer grown on a (110)-oriented STO substrate. The heterostructure is then immersed in a light acid solution, which is used to selectively etch the LSMO sacrificial layer, thus separating the (110)-STO thin film and the single crystal substrate. The freestanding (110)-oriented STO thin film (FS-STO) is then lifted off and transferred onto another (110)-oriented STO substrate, forming a natural but adjustable twisted angle (denoted as ϕ). In this manner, a new template composed of (110)-oriented STO but with an artificial twist angle can be delivered. In the article, multiferroic BiFeO_3 (BFO) is chosen to demonstrate the growth of the twisted lateral homostructures. As shown in the topography images of BFO on the pristine STO region, BFO on the FS-STO region and the twisted boundary in **Fig. 1(b)**, the stripe patterns that strictly follow the [001] direction of the BFO serve as direct evidence distinguishing the twist angles of the two identical epitaxial segments. This suggests that the twisted oxide lateral homostructures could be successfully fabricated using weave epitaxy. The structural details of the twisted lateral homostructures have been analyzed and verified *via* high-resolution X-ray diffraction (XRD) at **TLS 13A1**, **TLS 17A1**, **TLS 17B1**, and **TPS 09A** of the NSRRC.

Yang's group has further demonstrated the controllability and generic capability of fabricating different twisted lateral homostructures. In terms of controllability, they created designer patterns to artificially control the arrangements of the ferroelectric polarizations and antiferromagnetic directions in BFO. The BFO thin film grown on the patterned twisted template exhibits an in-plane twisted angle of 90° with respect to their individual [001] directions. As shown in **Fig. 2(a)**, piezo-force microscopy (PFM) analysis with respect to different cantilever orientations was carried out to identify the arrangement of the ferroelectric domains. Additionally, to investigate the direction of the antiferromagnetic axes in the patterned BFO(110) thin film, X-ray linear absorption spectroscopy (XLAS) measurement on the Fe $L_{2,3}$ -edge was carried out at the **TPS 45A**, as shown in the results in **Figs. 2(b) and 2(c)**. The controllable arrangements of both the ferroelectric and antiferromagnetic axes validate the feasibility of designing lateral crystalline orientation/domain patterns and related homostructures with conjunction twisted-angle tunability. To examine the generic capability of weave epitaxy, they extended the same concept to the classic high-temperature superconductor, $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ (YBCO). The artificially designed twisted YBCO lateral homostructures with controlled crystal arrangements and representative d_{z^2} orbital configurations are schematically illustrated in **Figs. 2(d) and 2(e)**. To reveal the structural nature in greater detail, further XRD data was collected at **TLS 13A1**, **TLS 17A1**, **TLS 17B1**, and **TPS 09A**. The XRD surface normal scans and phi-scans along off-normal planes of YBCO grown on (110)_{FS}- and (001)_{SUB}-oriented STO areas (**Fig. 3(f)**) both affirm the well-defined crystal structure and lattice symmetry of the crystals grown on the designed twisted templates underneath. These results indicate the crystal geometry of other complex oxides could also follow corresponding twisted frames and thus validates the universal capability of manufacturing twisted lateral systems using weave epitaxy.

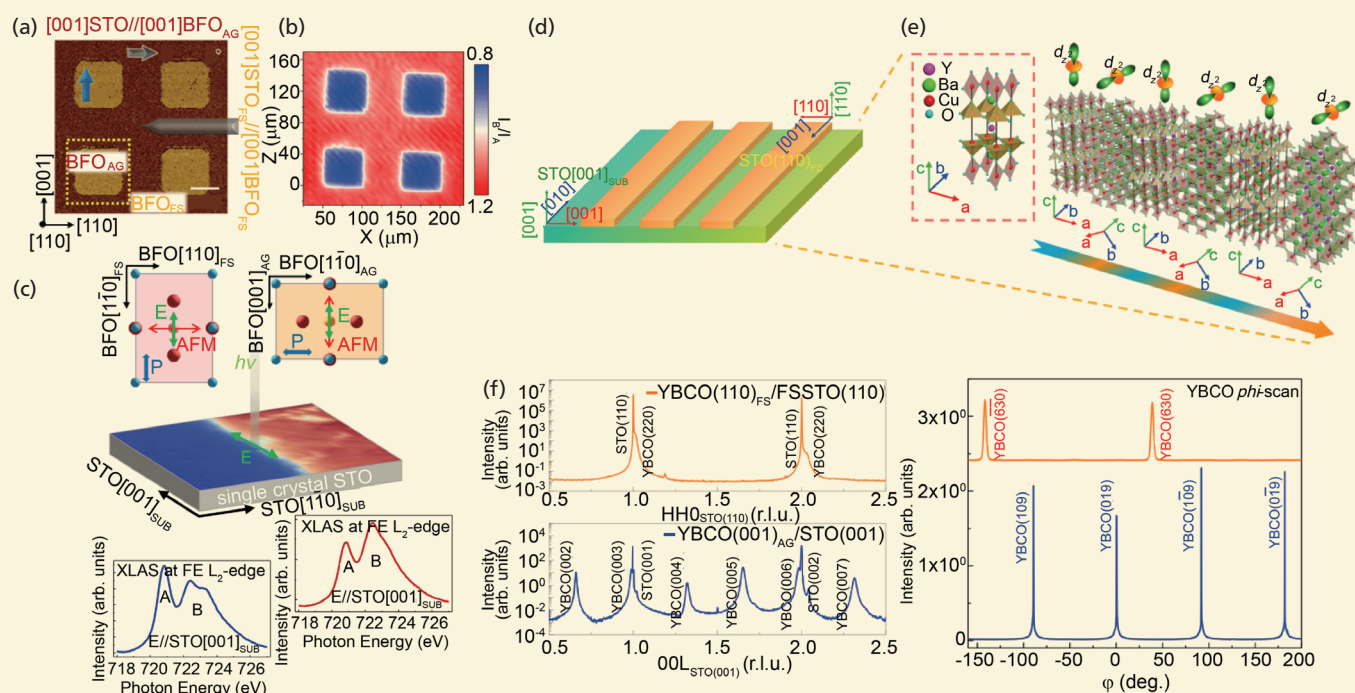


Fig. 2: Twisted oxide lateral homostructures with orientation and orbital conjunction tunability. (a) PFM images of a designed 90° twisted (110)-BFO. (b) XLAS mapping of the patterned 90° twisted (110)-BFO. (c) Fe $L_{2,3}$ -edge XLAS spectra of the BFO_{AG} and BFO_{FS} areas. (d) Schematic of the designed twisted YBCO homostructures. (e) Corresponding orbital arrangement of the designed twisted YBCO homostructure. (f) XRD line scan along the surface normal direction and phi-scan of the freestanding (orange) and pristine (blue) areas. [Reproduced from Ref. 1]

In summary, Yang and his group has demonstrated a novel approach to the synthesis of twisted lateral homostructures with orientation and phase conjunction turnabilities. This is a significant leap ahead of the conventional concept of epitaxy. With a patterned prototype device, they further demonstrated that the proposed approach is not only compatible with conventional lithography and etching processes, but also could be universally applied for fabricating various twisted complex materials. The results demonstrate the excellent controllability and unbounded conjunction tunability of the lateral homostructures using this method, which was subsequently named “weave epitaxy”. Such an approach not only provides a new way to design twisted lateral homostructures but also depicts an entirely different conceptual scene for epitaxial growth. (Reported by Yu-Chen Liu, National Cheng Kung University)

*This report features the work of Jan-Chi Yang and his collaborators published in Nat. Commun. **13**, 2565 (2022).*

TPS 09A Temporally Coherent X-ray Diffraction

TPS 45A Submicron Soft X-ray Spectroscopy

TLS 13A1 X-ray Scattering

TLS 17A1 X-ray Powder Diffraction

TLS 17B1 X-ray Scattering

- XRD, XAS
- Materials Science, Condensed-matter Physics

Reference

1. P. C. Wu, C. C. Wei, Q. Zhong, S. Z. Ho, Y. D. Liou, Y. C. Liu, C. C. Chiu, W. Y. Tzeng, K. E. Chang, Y. W. Chang, J. Zheng, C. F. Chang, C. M. Tu, T. M. Chen, C. W. Luo, R. Huang, C. G. Duan, Y. C. Chen, C. Y. Kuo, J. C. Yang, Nat. Commun. **13**, 2565 (2022).

CaCu₃Ru₄O₁₂: An Unusually High-Kondo-Temperature Transition-Metal Oxide

Using a combination of bulk sensitive hard and soft X-ray electron spectroscopy, the authors confirm that CaCu₃Ru₄O₁₂ is a high Kondo temperature metallic oxide.

The Kondo effect involves the scattering of conduction-band electrons in a metal by localized magnetic impurities. It was originally observed as a minimum in electrical resistivity for a metal with magnetic impurities at low temperatures, along with coupled changes in the magnetic susceptibility and specific heat. Subsequently, the Kondo effect has been observed in many Ce, Yb, and U-based materials in which the localized magnetic 4f electrons hybridize with the conduction-band electrons and can lead to heavy fermion behavior.¹ However, the Kondo effect and heavy fermion behavior are rarely observed in oxides and LiV₂O₄ is considered to be one such material.² More recently, the transition-metal oxide CaCu₃Ru₄O₁₂ (CCRO) has been considered as a Kondo material with heavy fermion behavior.³ However, this hypothesis has been contested and debated in the literature.⁴ In this highlight, through an international collaboration spanning Germany, Taiwan, Japan, Korea and Austria, researchers carried out a comprehensive study to determine whether

CCRO can be best described as a high-Kondo-temperature transition-metal oxide.⁵

The authors first carried out a careful comparison of the magnetic susceptibility of CCRO with that of CaCu₃Ti₄O₁₂ (CCTO). While the magnetic susceptibility of CCRO matched the data published in the literature, it exhibited an order of magnitude lower magnetic susceptibility compared with that of CCTO. This result implies that CCRO is nonmagnetic, in which case the Cu ions must be monovalent (with a non-magnetic 3d¹⁰ configuration) or trivalent such as a nonmagnetic insulator NaCuO₂. To confirm whether Cu ions in CCRO are magnetic, the authors carried out Cu L-edge X-ray absorption spectroscopy (XAS) and Cu 2p–3d resonant photoelectron spectroscopy (PES) at **TPS 45A1**, the Submicron Soft X-ray Spectroscopy beamline at the NSRRC, as shown in **Fig. 1** (see next page). The peak positions and line shape of the Cu L-edge XAS and the on-resonance 2p–3d PES spectra are typical of divalent Cu; hence, Cu in CCRO is not monovalent or trivalent.